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ENCIT2018-0085-HEAT TRANSFER WITH PHASE CHANGE AROUND FINNED TUBE SUBMERSED IN PCM

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Abstract. *Phase change materials are occupying a leading position in many applications especially in energy storage, thermal insulation and many other applications. Although most preferred among other thermal storage materials because of their high capacity for energy storage and nearly isothermal behavior during charging and discharging processes they are penalized due to their low thermal conductivity and consequently the difficulty in transferring heat to them or retrieving stored energy from them. This led to intensify research activities to investigate means for increasing the PCM effective thermal conductivity and enhance heat transfer rates during the process of charging and discharging. One of these methods is the use of extended surfaces or finned tubes. The present paper presents the results of a numerical and experimental investigation on a finned tube submersed in liquid PCM at its phase change temperature while a cold fluid at lower temperature flows inside the finned tube. A conduction model is used to represent the heat transfer process with phase change using the enthalpy method and finite difference scheme. The home-built numerical code is developed, tested, optimized and validated against experimental results. It is then used to predict the interface position, interface velocity and the time for complete phase change. The numerical predictions are found to agree reasonably well with the experimental result. Fins are found to increase the interface position, solidified PCM mass, and interface velocity and to decrease the time for complete phase change of the PCM.*

Keywords: *Phase change; Energy storage; finned tube; interface velocity; time for complete phase change.*

1. INTRODUCTION

Latent heat thermal energy storage systems are effective in comparison to sensible heat storage systems due to their high storage capacity and almost their isothermal behavior during the discharge process. Their main disadvantage is their low thermal conductivity which usually leads to low charging and discharging rates and hence decreasing the overall performance of the system. This negative impact can be attenuated by employing enhancement techniques which received significant attention in recent years. Among the techniques for heat transfer enhancement in phase change materials one can include PCM dispersed with high conductivity particles, shell and tube systems, micro-encapsulation of the PCM, axial finned tubes, radial finned tubes and internally and externally finned tubes, finned plane surfaces among others.

Erek *et al.*, (2005) realized numerical and experimental study on thermal energy storage with finned tubes. As a result of varieties of investigations on latent heat storage systems the shell-and-tube type heat exchanger is the most promising device as a latent heat system that requires high efficiency for a minimum volume. One of the methods used for increasing the rate of energy storage is to increase the heat transfer surface area by employing finned surfaces. In their study, they solved the governing equations for the heat transfer fluid, pipe wall and phase change material and numerical simulations were performed to investigate the effects of fin parameters such as fin spacing and fin diameter, and flow parameter such as Reynolds number and inlet temperature of the working fluid and compare the numerical predictions with experimental results. The influences of the variables on energy storage were presented and discussed.

Fan *et al.*, (2011) presented a literature review of experimental/computational studies to enhance the thermal conductivity of phase change materials (PCM) conducted over many decades. Thermal management of electronics for aeronautics and space exploration appears to be the original intended application, with later extension to storage of thermal energy for solar thermal applications. The review focuses on studies that concern with positioning of fixed, stationary high conductivity inserts/structures. Copper, aluminum, nickel, stainless steel and carbon fiber in various forms (fins, honeycomb, wool, brush, etc.) were generally utilized as the materials of the thermal conductivity promoters.

Tay *et al.*, (2012) validated experimentally a CFD model on a vertical finned tube heat exchanger with phase change. It was found that the model matches well with the experimental results.

Rahimi *et al.*, (2014) presented the results of an experimental investigation of phase change inside a finned-tube heat exchanger. The motivation of their study was to design and construct a storage unit and to compare it with a finless heat exchanger. A series of experiments were conducted to investigate the effect of increasing the inlet temperature and flow rate on the charging and discharging processes of the phase change material. It is shown that, using fins in phase change process enhances melting and solidification processes.

Parry *et al.*, (2014) reported on the development of a computationally efficient numerical simulation model for a shell-and-tube thermal energy storage system, where the heat transfer occurs between a fixed mass of phase-change material (PCM) in contact with a tube through which flows a high-temperature fluid. Simulations of the conjugate heat transfer and melting / solidification of the PCM for a range of heat exchanger designs, including single-tube control/baseline, single tube with longitudinal and circular fins, and multitube configurations, were undertaken and the numerical results were validated using experimental data. Comparison of heat transferred during charging and discharging phases between the one-dimensional and refined two-dimensional predictions was in agreement to within 8.5%, indicating the usefulness of the one-dimensional model and the adopted effective conduction approach.

Hosseini *et al*., (2015) reported on the results of thermal analysis of PCM containing heat exchanger enhanced with normal annular fins. In this study, the effect of fins' height and Stefan number on the performance of a shell and tube heat exchanger which contains a phase change material was investigated numerically and experimentally. Melting time, solidification time, liquid mass fraction, melting and solidification front and temperature distribution in the longitudinal, radial and angular directions were analyzed. The results show that the melting time decreases with the increase of Stefan number and that increasing fins' height influences the solidification time more significantly than melting.

Joybari *et al*., (2017) conducted a study of heat transfer enhancement of phase change materials by fins under simultaneous charging and discharging conditions. In their study, they utilized extended surfaces (longitudinal fins) and developed a numerical model to study the performance of a triplex tube heat exchanger equipped with a PCM under simultaneous charging and discharging. The governing equations were solved numerically by using ANSYS Fluent v16.2. The results indicated that since the buoyancy forces induce upward melted PCM motion, the inner hot tube requires fins on its lower half, while the outer cold one should be extended from its upper half. It was concluded that the case with 3 hot tube fins and one cold tube fin is most compatible with natural convection and provides the best performance under simultaneous discharge and charge conditions.

Ibrahim *et al*., (2017) presented a critical review on heat transfer enhancement of phase change materials for thermal energy storage applications. Their paper presents a state-of-the-art review on various techniques of heat transfer enhancement in latent heat thermal energy storage systems. Heat transfer enhancement in latent heat thermal energy storage systems systems can be achieved through either geometric configuration and/or thermal conductivity enhancement. The use of extended surfaces such as fins or heat pipes is a common technique for heat transfer enhancement in these systems. They also studied the thermal conductivity enhancement techniques, which include the use of porous materials, nanoparticles with high thermal conductivity, and low-density materials.

In this study, a model for the solification of PCM around a radial finned tube with constant wall temperature is developed and solved numerically. The model is based upon pure heat conduction formulation and the enthalpy method. The finite difference approach and the alternating direction implicit scheme were used to discretize the system of equations and the associated boundary, initial and final conditions. A home-built numerical code is developed and optimized, validated and then used to investigate the effects of the diameter of fin and the tube wall temperature on the interface position, the interface velocity, the solidified mass fraction and the time for complete phase change.

2. PROBLEM MODELING

The problem under consideration can be represented by a horizontal tube fitted with external radial fins and submersed in liquid phase change material (PCM) at its phase change temperature. A circulating cold fluid flows along the tube forming a solid layer of PCM over the tube and fins surfaces. It is required to determine the effects of the fin on the phase change parameters of this process. To be able to handle this problem assume some simplifying assumptions including that the PCM is pure and of well-defined temperature varying properties, constant surface temperature over the tube and heat transfer process dominated by conduction.

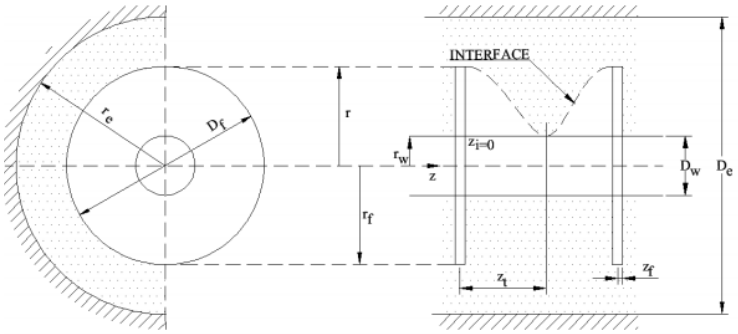

Figure 1. Layout of the problem.

The energy equation in cylindrical coordinates for the PCM solid phase is:

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_s \frac{\partial T_s}{\partial r} \right) + \frac{\partial}{\partial z}\left(k_s \frac{\partial T_s}{\partial z} \right) \tag{1}$$

The energy equation for the PCM liquid phase is:

$$\rho_l c_l \frac{\partial T_l}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_l \frac{\partial T_l}{\partial r} \right) + \frac{\partial}{\partial z}\left(k_l \frac{\partial T_l}{\partial z} \right) \tag{2}$$

The boundary conditions at the interface can be written as:

$$\left(k_s \frac{\partial T_s}{\partial r} - k_l \frac{\partial T_l}{\partial r} \right)\left(1 + \left(\frac{\partial s}{\partial z} \right)^2 \right) = \rho_s L \frac{\partial s}{\partial t}; \qquad r = s(t) \tag{3}$$

$$\begin{array}{lll} T_s = T_l = T_m & & r = s(t) \\ At & \mathrm{r} = \mathrm{r_w}; & T = T_w \\ At & \mathrm{r} = \mathrm{r_e}; & \dfrac{\partial T}{\partial r} = 0 \\ At & \mathrm{z} = \mathrm{z_i} = 0; & \dfrac{\partial T}{\partial z} = 0 \\ At & \mathrm{z} = \mathrm{z_t}; & \dfrac{\partial T}{\partial z} = 0 \end{array} \tag{4}$$

The initial and final conditions can be written as:

$$\begin{array}{lcl} T(r,z,t=0) & = & T_m + \Delta T \\ T(r,z,t_f) & = & T_m - \Delta T \end{array} \tag{5}$$

where ΔT is half of the phase change temperature range.

The above phase change problem is solved numerically following the enthalpy approach adopted in Ismail, *et al.*, 2001. The above model based upon pure heat conduction formulation is treated by the enthalpy method, while the finite difference approach and the alternating direction implicit scheme were used to discretize the system of equations and the associated boundary, initial and final conditions. The details are omitted here for brevity. The set of equations of the model and the boundary and initial conditions were implemented in a home-built computational code which was thoroughly tested and optimized. The input parameters used are finned copper tube of 1 m length and 15 mm tube diameter, the PCM is water and the range of phase change is 0.1°C. Numerical tests were realized to ensure that the results are independent of the number of grid points. The simulations were realized for number of grid points of 100 and for convergence precision of 0.0001.

3. EXPERIMENTAL RIG AND TEST PROCEDURE

The general scheme of the experimental system is shown in Figure 2 and 3 is composed of a compression refrigeration circuit and a secondary circuit for cooling the working fluid (Ethanol). The test set up is composed of a compression refrigerant circuit, secondary fluid circuit, coiled tube heat exchanger submersed in the secondary fluid tank, the test section of the finned tube which is connected to the secondary fluid circuit. The secondary fluid is Ethanol cooled by the refrigerant flowing through the coiled tube heat exchanger and its temperature and mass flow rate are controlled as required.

The test section is of rectangular shape built from 15 mm thick acrylic sheet with the test tube extended across the test section filled with PCM (water) whose initial temperature can be varied as desired. High resolution digital camera is used to photograph the finned tube and the reference scale. The reference scale is used to convert the image dimensions to real values. Calibrated thermocouples type T, are fixed at entry and exit of the finned tube, in the PCM test tank, along the finned tube and in the secondary fluid tank. Calibration of thermocouples and orifice plate were realized and error analysis and propagation in the results were done and the final results indicate a calibration error in the thermocouples of ± 0.5 °C, image conversion precision of ± 0.1mm while the mass flow rate (measured by a calibrated orifice plate) of ± 10^{-4} kg/s.

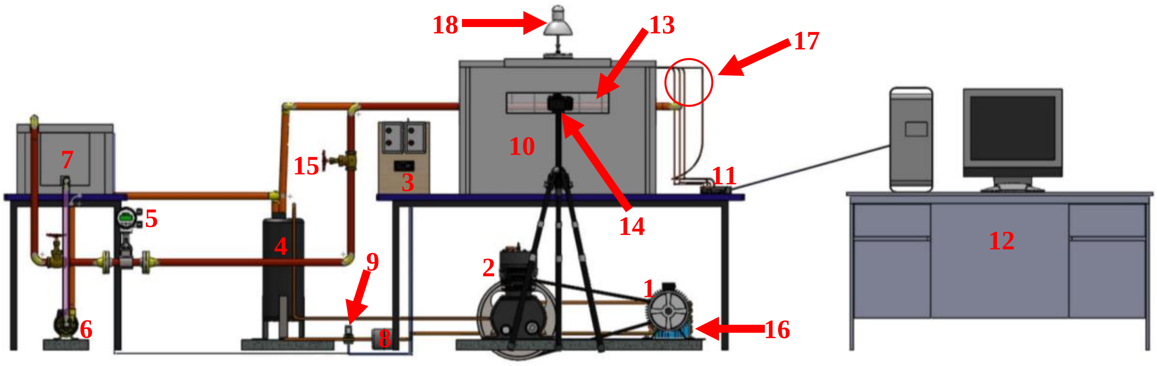

Figure 2. Test bench scheme. 1:Electric motor; 2:Compressor; 3:Set point; 4:Heat exchanger; 5: Flow meter; 6:Pump; 7:Alcohol tank; 8:Oil filter; 9:Solenoid valve; 10:Test section; 11:Signal acquisition board; 12:Computer; 13:Finned tube: 14:Digital camera; 15:Valve; 16:Condensing unit; 17:T-type thermocouples; 18:Lamp

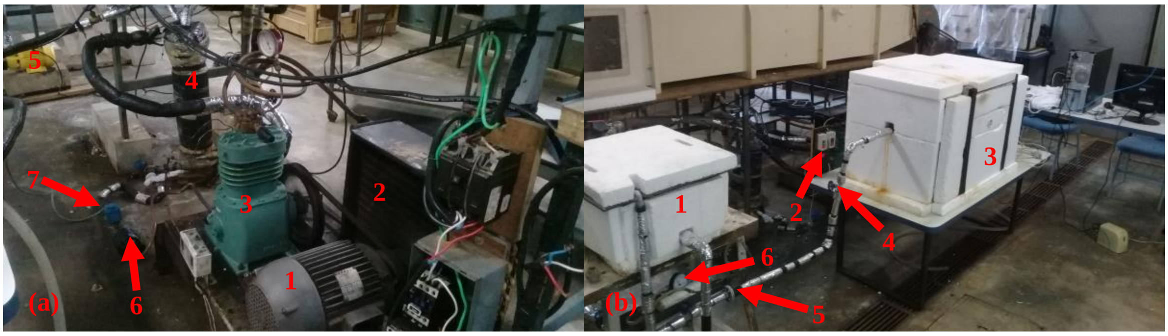

Figure 3. Real test bench scheme with several components of refrigeration system. (a) 1:Eletric motor; 2:Condensing unit; 3:Compressor; 4:Heat exchanger; 5:Pump; 6:Oil filter; 7:Solenoid valve. (b) 1: Alcohol tank; 2: Set point; 3: Test section; 4:Valve; 5:Orifice plate; 6:Flow meter

Measurements were usually taken when the desired testing conditions were achieved, that is the temperature of the working fluid in the test finned tube, temperature of the Ethanol tank, temperature of the PCM, and the mass flow rate of the secondary fluid. Under these initial conditions the chronometer is started after registering all initial conditions. During the first hour each 2 minutes period all the readings of the measurement points are registered and a photograph of the finned tube is taken. During the second and third hours measurements are registered each 15 minutes interval. After that, the time interval is increased to 30 minutes until the end of the test. The test is considered terminated when no change in temperature or interface position is registered along three successive time intervals. The interface position is tracked and converted to real dimension by using the program Tracker and the reference scale as shown in Figure 4.

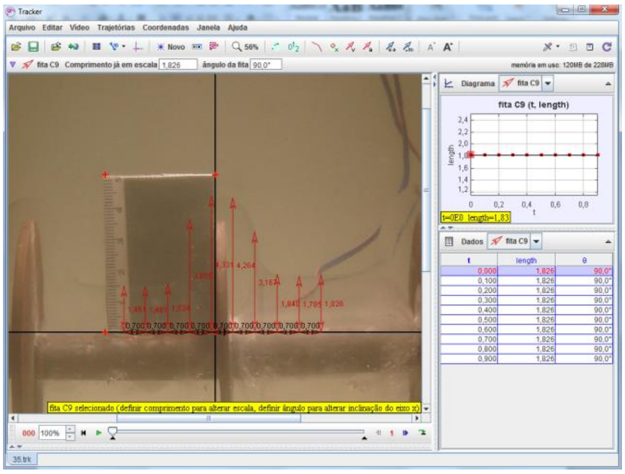

Figure 4. Tracker software with the finned tube positioned for digitalization of the interface position

3. RESULTS

Some of the experimental results obtained for the bare and finned tube will be presented in this section. Figure 4 shows the variation of the radial interface position with time for the case of bare tube (without fins). The experiment was realized for different mass flow rates of the circulating ethanol and tube wall temperature of -11.82 ^{o}C. As can be seen the gradient of the interface position with respect to time continuously decreases due to the increase of the thermal resistance between the tube wall and the PCM around the tube until finally reaches almost zero. Also one can observe that the increase of the mass flow rate increases the interface position due to the increase of the internal Reynolds number which increases the internal heat transfer coefficient.

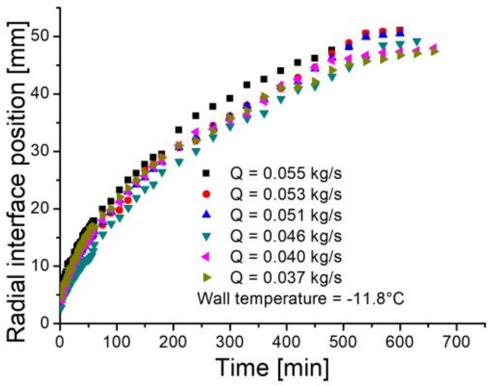

Figure 5. Variation of the radial interface position with time for different mass flow rates for the case of finless tube.

Figure 6 shows the variation of the interface velocity for the same conditions as in Figure 5. One can observe that the interface velocity decreases with time due to the increase of the thermal resistance. Also the increase of the mass flow rate increases the interface velocity but the differences are too small due to the limited mass flow rate realized in the tests.

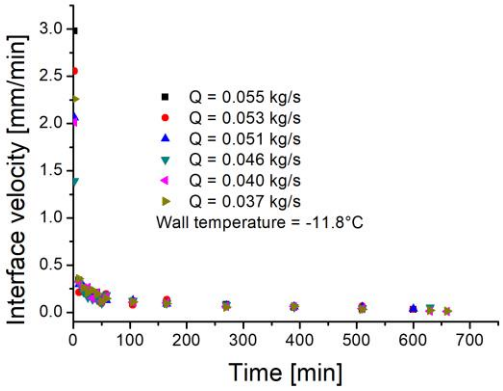

Figure 6. Variation of the interface velocity with time for different mass flow rates for the case of finless tube.

The mass of formed ice is obtained from digitalizing the photographs by using the software Tracker. Figure 7 shows the variation of formed mass with the increase of the mass flow rate of the ethanol and for different wall temperatures. As can be seen the decrease of the tube wall temperature increases the mass of the formed ice due to the increase of the temperature gradient between the surface of the tube wall and the PCM surrounding the tube. Also one observes the increase of the formed ice with the increase of the mass flow rate which causes the increase of Reynolds number and hence the internal heat transfer coefficient. This is in agreement with the above discussion. The stored energy can be evaluated using the results shown in Figure 8 where the sensible heat was ignored because it is very small in comparison with the latent heat.

Figure 9 shows the variation of the time for complete phase change with the mass flow rate of the ethanol and with the wall temperature. As can be seen the increase of the mass flow rate reduces the time for complete phase change (solidification of PCM) due to the increase of the internal heat transfer coefficient as mentioned before. The decrease of the tube wall temperature has the effect of increasing the temperature difference between the tube surface and PCM around it and consequently reduces the time for complete phase change of the PCM.

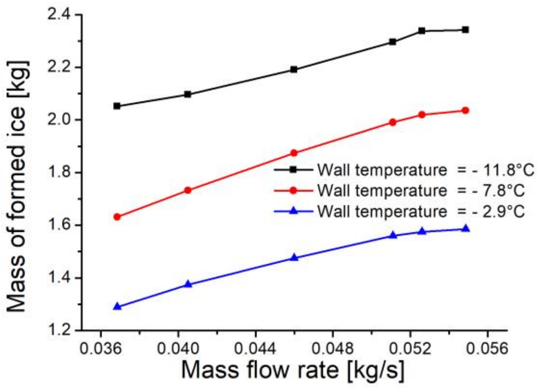

Figure 7. Variation of mass of formed ice with mass flow rate for the case of finless tube.

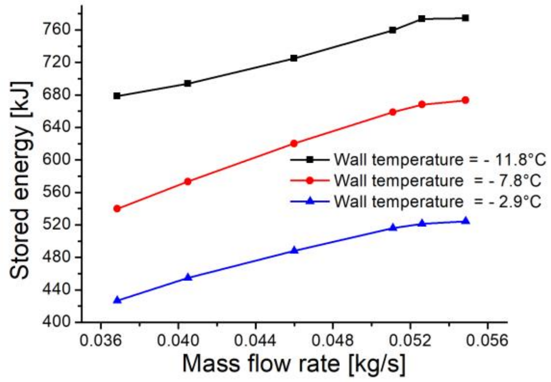

Figure 8. Variation of stored energy with mass flow rate for the case of finless tube.

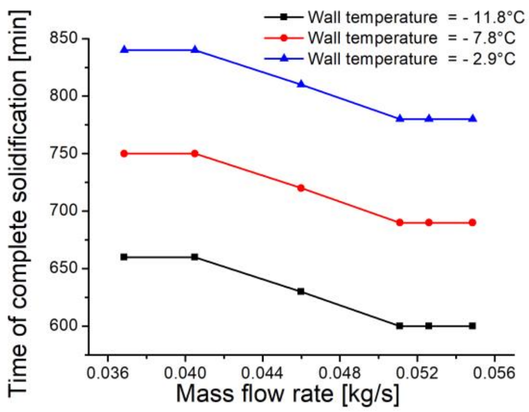

Figure 9. Variation of the time for complete solidification with mass flow rate for the case of finless tube.

Similar effects are found in the case of tube fitted with 90 mm diameter radial fin except that interface position is bigger and the interface velocity is also bigger. The same mechanisms of heat transfer are the deriving force for PCM solidification enhanced by the increase of the surface area due to the fin. Figure 10 shows the mass of formed ice while Figure 11 shows the accumulated energy as latent heat in the solidified mass of PCM. Figure 12 shows the time for complete phase change of the PCM and as was mentioned before, the increase of the mass flow rate and the reduction of the tube wall temperature are now associated with the increase of the heat transfer to provoke more reduction of the time for complete phase change as can be seen in Figure 11.

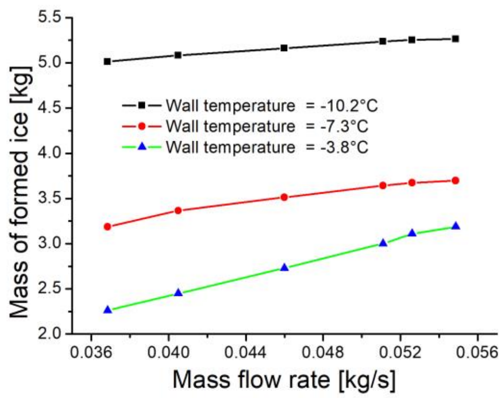

Figure 10. Variation of the mass of formed ice with mass flow rate for the case of tube with 90 mm fin diameter.

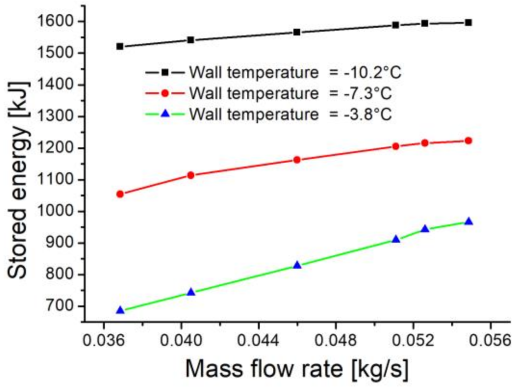

Figure 11. Variation of the stored energy with mass flow rates for the case of tube with 90 mm fin diameter.

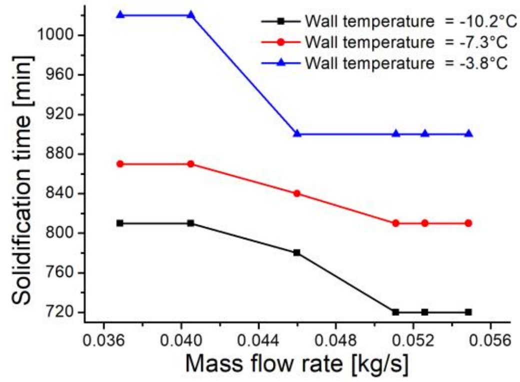

Figure 12. Variation of the time for complete solidification with mass flow rate for the case of tube with 90 mm fin diameter.

As was mentioned a home made numerical code was written, optimized and tested for different working conditions. Because of lack of experimental results we proceeded to obtian experimental results to compare and validate the numerical predictions and the home-built code. Figure 13 shows a comparison between the predicted interface position and experiments for the case of finned tube. The agreement is relatively good except in the initial stages where the difference can be attributed to the thermal inertia of the system. Similar effects are found in Figure 14 of the interface velocity where in the initial itervals the numerical predictions overestimate the interface velocity. This can be attributed to the fact that the volume of the PCM tank at entry and exit is not active and occupied by loose isolante material which allowing some water to be retained in the space between the loose insulation and the acrylic walls of the PCM tank. The numerical model does not account for the residual thermal inertia of this additional mass. Reduction of the volume of the tank can reduce these differences and possibly eliminate these effects. Figures 15 and 16 show similar results.

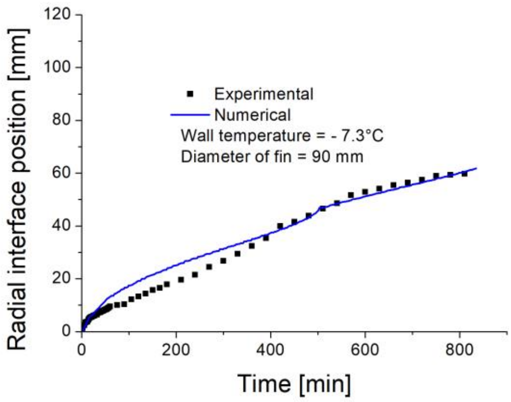

Figure 13. Comparison of the predicted interface position with experiments for the case of finned tube.

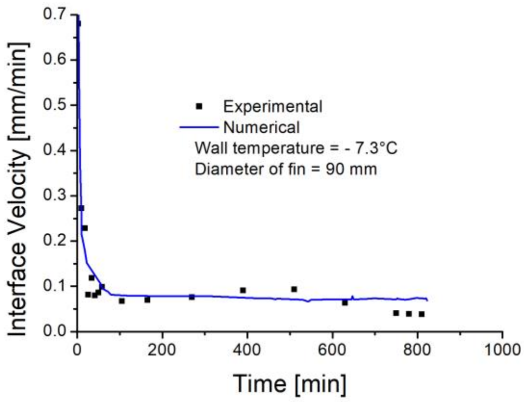

Figure 14. Comparison of the predicted interface velocity with experiments for the case of finned tube.

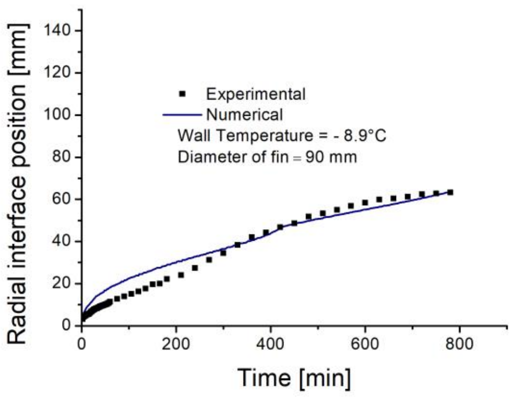

Figure 15. Comparison of the predicted interface position with experiments for the case of finned tube.

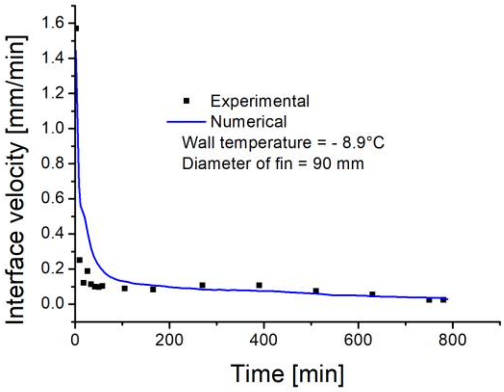

Figure 16. Comparison of the predicted interface velocity with experiments for the case of finned tube.

To evaluate the effects of incorporating radial fins external to the tube results are presented for the interface position after four hours of tests for the cases of finned and finless tubes as shown in Figure 17. One can observe the notable increase in the interface position due to the increase of the heat transfer area caused by the fin. One can also observe that the reduction of the wall temperature and hence increases the position of the interface enhancing the mass of formed ice as can be observed in Figure 18.

The interface velocity is also enhanced due to incorporating fins on the tube where the cold ethanol is flowing. One can also observe that reducing the tube wall temperature increases the interface velocity due to the increase of the thermal gradient between the increased finned tube surface and the PCM. Similar results are found for other time intervals and are ommited for the sake of brevity.

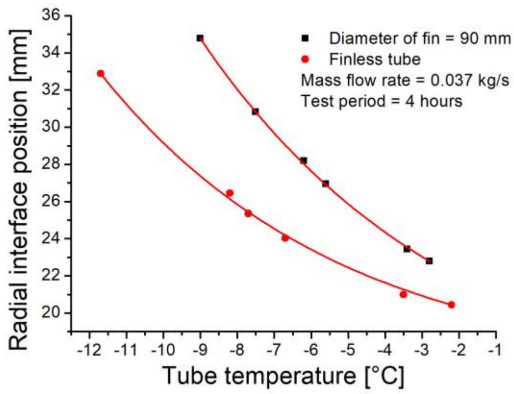

Figure 17. Comparison of the radial interface position for finned and finless tube after 4 hours of test.

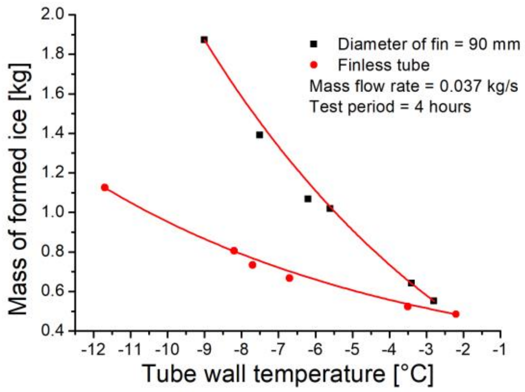

Figure 18. Comparison of the mass of formed ice for finned and finless tube after 4 hours of test.

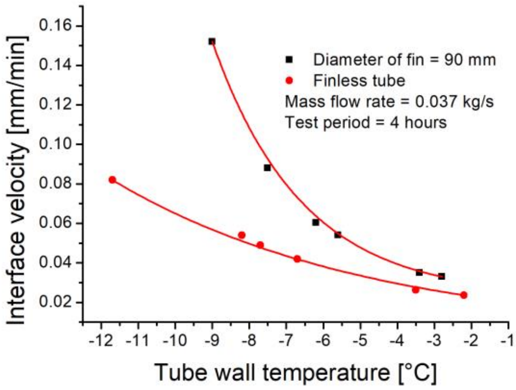

Figure 19. Comparison of the interface velocity for finned and finless tube after 4 hours of test.

5. CONCLUSIONS

This paper presents the results of a numerical and experimental study of the effects of fins on the problem of solidification of PCM around a tube submersed in a tank full with PCM in the liquid phase. A home-built program based on the proposed conduction model was constructed, tested, optimized and validated against experimental results indicating relatively good agreement. It is found that fins increase the interface position, increase the solidified PCM mass, increase the associated accumulated energy, enhance the interface velocity and reduce the time for complete phase change of the PCM.

6. ACKNOWLEDGEMENTS

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